

Are there age spreads in star forming regions?

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Abstract A luminosity spread at a given effective temperature is ubiquitously seen in the Hertzsprung-Russell (HR) diagrams of young star forming regions and often interpreted in terms of a prolonged period (≥ 10 Myr) of star formation. I review the evidence that the observed luminosity spreads are genuine and not caused by astrophysical sources of scatter. I then address whether the luminosity spreads necessarily imply large age spreads, by comparing HR diagram ages with ages from independent clocks such as stellar rotation rate, the presence of circumstellar material and lithium depletion. I argue that whilst there probably is a true luminosity dispersion, there is little evidence to support age spreads larger than a few Myr. This paradox could be resolved by brief periods of rapid accretion during the class I pre main-sequence phase.

1 Introduction

When newly born stars emerge from their natal clouds as class II and class III pre main-sequence (PMS) objects, they can be placed in a Hertzsprung-Russell (HR) diagram. Low-mass ($< 2 M_{\odot}$) stars take 10–100 Myr to descend the Hayashi track and settle onto the zero-age main-sequence, so the HR diagram can be used, in combination with theoretical models, to estimate individual ages for PMS stars or construct the age distribution of a group of PMS stars. The HR diagrams of young star forming regions (SFRs) usually have an order of magnitude range of luminosity at a given effective temperature (T_{eff} , see Fig.1), and this luminosity dispersion is often interpreted as star formation that has been ongoing for ≥ 10 Myr within a single SFR or young cluster (e.g. for young, nearby SFRs – Palla & Stahler 1999,

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2000; for massive young clusters – Beccari et al. 2010; or even for resolved star clusters in other galaxies – Da Rio, Gouliermis & Gennaro 2010a).

The presence and extent of any age spread is an important constraint on models of star formation. A significant (≥ 10 Myr) spread would favour a “slow” mode, where global collapse is impeded by, for example, a strong magnetic field (e.g. Tassis & Mouschovias 2004). Age spreads that were ≤ 1 Myr however, could be explained by the rapid dissipation of turbulence and star formation on a dynamical timescale (e.g. Elmegreen 2000). The reality or not of age spreads is also important from a practical point of view. Ages from the HR diagram are used to understand the progression of star formation (e.g. triggering scenarios, collect-and-collapse models) and the age-dependent masses estimated from an HR diagram are usually the only way of determining the initial mass function. In this short review, I ask:

1. Are the luminosity spreads (at a given T_{eff}) in the HR diagram real?
2. If so, do these necessarily imply a wide spread of ages within an individual SFR?

2 Luminosity spreads?

Hartmann (2001) identified many sources of astrophysical and observational scatter that contribute to an *apparent* spread in the luminosities of PMS stars at a given T_{eff} . These include the likelihood that many “stars” are unresolved multiples; that individual stars may be subject to a range of extinction and reddening; that PMS stars can be highly variable; that the luminosity contributed by accretion processes could vary from star-to-star; that in (nearby) SFRs the stars are at a range of distances; and that placing stars on a HR diagram requires temperature (or spectral type or colour) and luminosity (brightness) measurements which have observational uncertainties. Hartmann concluded that efforts to infer star formation histories would be severely hampered by these effects and that the luminosity and hence age spreads claimed by Palla & Stahler (2000), among others, must be extreme upper limits. Hillenbrand, Bauermeister & White (2008) showed that it is difficult to verify or indeed quantify luminosity spreads, and hence infer age spreads, unless (a) observational uncertainties are small and (b) both the *size and distribution* of other astrophysical sources of luminosity dispersion are well understood.

One approach to tackle these difficulties is to quantify spreads that could be contributed by individual sources of dispersion and model the outcome. Burningham et al. (2005) used photometric measurements at more than one epoch to empirically assess the affects of variability on two young SFRs (σ Ori and Cep OB3b) with significant (compared to observational uncertainties) scatter in their colour-magnitude diagrams (CMDs). This approach takes account of correlated variability in colours and magnitudes and the non-Gaussian distribution of variability-induced dispersion. A coeval population was simulated using the observed levels of variability, the likely effects of binarity and observational errors. This model was found to significantly *underpredict* the observed dispersion. In other words, variability (on timescales of years or less), binarity and observational error could only account for

a small fraction of the luminosity dispersion. On the other hand, Slesnick, Hillenbrand & Carpenter (2008) examined the slightly older Upper Sco SFR and showed that the large observed luminosity spreads could perhaps be entirely explained by a coeval population affected by a combination of observation errors, distance dispersion and binarity. However, the additional dispersion (particularly due to distance uncertainties) was so large in this case that additional scatter equivalent to a real age dispersion of ± 3 Myr remained a possibility.

A more sophisticated statistical approach has been taken by Da Rio, Gouliermis & Gennaro (2010a) who, using a maximum likelihood method akin to that proposed by Naylor & Jeffries (2006), fitted a 2-dimensional synthetic surface density to the CMD of a SFR in the Large Magellanic Cloud. The model includes contributions from unresolved binarity, variability, differential extinction and accretion. These authors conclude that the luminosity spread in the CMD is too large to be accounted for by the “nuisance” sources of dispersion and interpret the additional scatter as a spread in ages of FWHM 2.8–4.4 Myr.

An alternative for investigating the reality of the luminosity dispersions is to examine proxies such as radius or gravity that would be expected to show a corresponding dispersion, but whose measurement is not so greatly affected by the additional astrophysical sources of scatter. An example is the use of rotation periods and projected equatorial velocities to estimate the projected radii, $R \sin i$, of PMS stars in the Orion Nebula cluster (ONC, Jeffries 2007). These measurements are largely unaffected by binarity, variability, differential extinction, distance or accretion. Assuming that spin-axes are randomly oriented, the distribution of $R \sin i$ can be modelled to estimate mean radii and the extent of any true spread in radius at a given T_{eff} . The results confirm that a factor of 2–3 (FWHM) spread in radius exists at a given T_{eff} and this concurs with the order of magnitude luminosity spread seen in the HR diagram of the same objects.

In summary, although there are few detailed investigations to draw on, the evidence so far suggests that the luminosity spreads seen in SFRs are mostly genuine. Only a fraction of the dispersion can be explained by observational uncertainties, variability, binarity and accretion.

3 Age Spreads?

If the luminosity dispersions are genuine, then it is natural to plot a set of HR diagram isochrones, estimate an age for each star and hence infer an age distribution. However it is possible that physical causes other than age could contribute to a real dispersion of luminosity in the HR diagram of young PMS stars. Accretion could perturb the evolution of the central star, inducing a luminosity spread even in a coeval population (Tout, Livio & Bonnell 1999). To investigate the fidelity of ages deduced from the HR diagram we can compare these ages with those estimated using independent clocks. These include the depletion of photospheric lithium, the evolution of stellar rotation and the dispersal of circumstellar material.

3.1 Lithium Depletion

Lithium is ephemeral in the photospheres of young, low-mass stars. Once the central temperature of a star reaches the Li ignition temperature, ($\sim 2.5 \times 10^6$ K) convective mixing leads to almost complete Li depletion unless the PMS star leaves the Hayashi track and develops a radiative core (see Jeffries 2006). In principle the level of Li in the atmosphere of a low-mass PMS star is a mass-dependent clock. Palla et al. (2005) and Sacco et al. (2007) have searched for Li-depleted stars that are bona-fide members of the Orion Nebula cluster and the σ Ori and λ Ori associations. They do find a few such objects (a few per cent of the total) and using models for Li depletion, infer ages for them of > 10 Myr, compared to HR diagram ages of 2–5 Myr for the bulk of the PMS population. These observations are consistent with the presence of a small fraction of older objects, co-existing with the bulk of the younger PMS population, arguing in favour of a large age spread.

Whilst this interpretation is possible, there are some problems. First, the bimodal distribution of Li abundances (i.e. most stars are undepleted with a small fraction of extremely Li-depleted objects) does not seem consistent with a smooth underlying distribution of ages and indeed contamination by older, non-members of the cluster has been suggested (Pflamm-Altenburg & Kroupa 2007). Second, although in some (but not all) cases, the Li-depletion age for these stars matches the HR diagram age, they are *not* fully independent age indicators. The central temperature of the star, which controls the Li-burning, will depend on the stellar radius (and hence luminosity in the HR diagram). If for some reason the star had a smaller radius than expected at a given age and therefore appeared older in the HR diagram, its central temperature would *also* be higher and it would have a greater capacity to burn Li.

3.2 Rotation rates

Young, PMS stars typically rotate with periods of 1–10 d. There is strong evidence that PMS stars with circumstellar disks and active accretion rotate more slowly on average than those without disks (e.g. Rebull et al. 2006; Cieza & Baliber 2007). A widely accepted idea is that stars which are accreting from a disk are braked by the star-disk interaction and held at a roughly constant spin period (Rebull, Wolff & Strom 2004). Once the disk disperses, or below some threshold accretion rate, the brake is released and the star spins up as it rapidly contracts along the Hayashi track. Thus, the rotation rate of PMS stars should broadly reflect the age of the population – an older population should have fewer strong accretors (see section 3.3), have had more time to spin-up, and hence should contain a greater proportion of fast rotators than a younger population. As the lifetime of accretion is of order a few Myr, then age spreads of 10 Myr should manifest themselves as big differences in the rotation period distributions of the “older” and “younger” populations.

This rotation clock has been investigated by Littlefair et al. (2011). They divided the PMS populations of several nearby SFRs into “old” (low luminosity) and

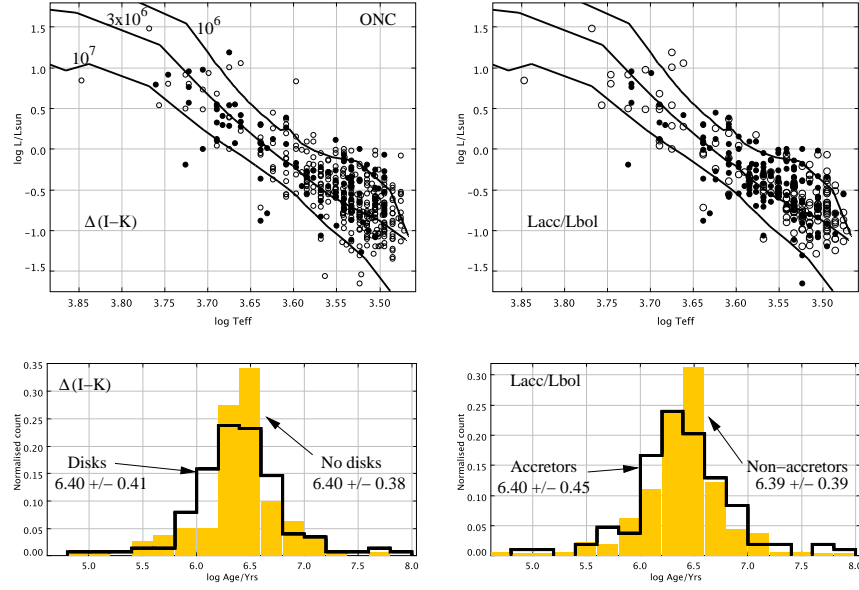


Fig. 1 The HR diagrams and inferred age distributions for samples of stars in the Orion Nebula cluster (ONC, data from Da Rio et al. 2010b). (Left) Upper plot shows isochrones (from Siess et al. 2000, labelled in Myr) and stars in the ONC separated by infrared excess. Open symbols are stars with $\Delta(I-K) > 0.3$ (data from Hillenbrand et al. 1998). Lower diagram shows the age distributions which have identical means and similar dispersions. (Right) A similar plot, but the open symbols are stars with $L_{\text{accrete}}/L_{\text{bol}} > 0.1$ (from Da Rio et al. 2010b). Again, the lower plot shows the age distributions of these samples are very similar.

“young” (high luminosity) samples and compared their rotation period distributions. The null hypothesis that the samples were drawn from the same distribution could be rejected at high significance levels, but the surprising result is that the faster rotating sample is actually the one containing the “young” objects. If the luminosity spreads were truly caused by an age spread, the “disk-locking” model would predict the opposite result. Littlefair et al. interpret this by assuming the populations in each SFR are coeval, but the luminosity spreads are introduced through differing accretion histories which also influence the stellar rotation rate (see section 4).

3.3 Disk dispersal

It is well known that the lifetime of circumstellar material around young PMS stars, traced by the fraction of objects exhibiting infrared excesses or accretion diagnostics, is on average a few Myr (e.g. Haisch, Lada & Lada 2001; Calvet et al. 2005; Jeffries et al. 2007; Hernández et al. 2008). The precise reasons for disk dispersal are

still unclear, but if the fraction of stars accreting strongly from a circumstellar disk does decrease with age then we would expect to see fewer active accretors among any older population *within a single SFR*.

Surprisingly little work has been done in this area. Hartmann et al. (1998) found that mass accretion rates did decline with increasing HR diagram age in Taurus and Chamaeleon. Bertout, Siess & Cabrit (2007) claimed that accreting classical T-Tauri stars in Taurus appeared significantly younger in the HR diagram than their weak-lined, non-accreting counterparts. On the other hand, Hillenbrand et al. (1998) find no correlation between age and the fraction of PMS stars in the ONC with near-infrared excesses. These studies are difficult because they are afflicted by a number of biases and selection effects.

In preparation for this review I examined a new catalogue of sources in the ONC by Da Rio et al. (2010b), which they claim to be complete to very low luminosities. They have estimated the luminosity and effective temperature of stars using a careful star-by-star estimate of accretion luminosity and extinction. Their catalogues give estimated masses and ages based on the models of Siess, Dufour & Forestini (2000). Figure 1 shows HR diagrams and deduced age distributions, where the samples have been divided according to (a) whether the $I - K$ excess over a photospheric colour is > 0.3 (data from Hillenbrand et al. 1998) or (b) whether the accretion luminosity is $> 0.1 L_{\text{bol}}$. Neither of these accretion/disk diagnostics shows a significant age dependence within the ONC, the mean ages and age distributions of the subsamples are indistinguishable. I am currently exploring any possible biases (e.g. dependences of age and the likelihood of possessing a disk on position within the cluster) that might explain these results.

Taking the results at face value suggests either: (i) Any true age spreads are much less than the few Myr characteristic timescale for the cessation of accretion and dispersal of circumstellar material and that a star's position in the HR diagram is *not* primarily age dependent. (ii) The scatter in the luminosities caused by the nuisance sources discussed in section 2 is so large that it erases the expected age-dependent decrease in the fraction of stars exhibiting accretion or disk signatures. For the reasons discussed in section 2 I regard this latter possibility as unlikely. In either case (i) or (ii) it would mean that the HR diagram could not be used to claim a large age spread or to estimate the star formation history.

4 Episodic accretion – a possible explanation

The idea that early accretion could alter a PMS star's position in the HR diagram and make it appear older have been around for some time (e.g. Mercer-Smith, Cameron & Epstein 1984; Tout et al. 1999). Recently it has been realised (e.g. by Enoch et al. 2009) that accretion onto very young stars may be transient or episodic, with very high accretion rates ($\sim 10^{-4} M_{\odot} \text{ yr}^{-1}$) occurring for brief periods of time ($\sim 100 \text{ yr}$). “Episodic accretion”, which would take place during the early class I T-Tauri phase, has been modelled by Vorobyov & Basu (2006) and its consequences for the PMS

HR diagram are explored by Baraffe, Chabrier & Gallardo (2009). They find that if the accreted energy is efficiently radiated away, then a short phase of rapid accretion compresses the PMS star, leading to a smaller radius and lower luminosity. The star will not relax back to the configuration predicted by non-accreting models for a thermal timescale ($\simeq 20$ Myr for the PMS stars I am discussing), and hence interpreting the HR diagram using non-accreting models would lead to erroneously large ages. A distribution of accretion histories in a coeval SFR could lead to a luminosity spread and the appearance of an age spread. As there may be no connection between accretion rates in the class I phase and later accretion as a class II T-Tauri star this could effectively randomise the ages determined from the HR diagram for young class II and class III PMS stars.

The model may also account for the apparent spin-down of PMS stars with age and for the small proportion of stars which appear to have anomalously high Li depletion. A PMS star with a true age of say 3 Myr, that had been subjected to relatively slow accretion rates during the class I phase would have contracted over 3 Myr from a larger radius and spun-up significantly. A coeval PMS star that had previously accreted at much high rates would already be smaller, less luminous and appear older, but would be relaxing back to its equilibrium configuration on a 20 Myr timescale and so would have undergone very limited contraction and spin-up (Littlefair et al. 2011). The same stars would have smaller radii and higher central temperatures than their slow-accreting counterparts and could therefore burn Li more readily (Baraffe & Chabrier 2010).

5 Conclusions

The evidence to date suggests that the luminosity dispersion seen in the HR diagrams of young SFRs has a significant component that cannot be attributed to “nuisance” sources such as binarity, variability and accretion. However, attempts to verify the consequent age spreads implied by the positions of PMS stars in the HR diagram have mixed success. In particular, the rotation rates of PMS stars and the fraction of stars showing active accretion or evidence for circumstellar material within a single SFR do not show the expected decrease with age. “Episodic accretion” potentially resolves this paradox – a very high rate of accretion during the class I phase could drive PMS stars out of equilibrium and towards smaller radii and lower luminosities. A distribution of early accretion rates would effectively scramble ages determined from the HR diagram for a population of class II and class III PMS stars.

If this scenario is borne out by further work, then the traditional HR diagram is a poor tool for estimating the ages of young (< 20 Myr) PMS stars and also perhaps for estimating age-dependent masses. Large scale survey work may instead have to rely on less precise but potentially more accurate clocks such as rotation rates or the presence of circumstellar material, although of course these may not be universal and could have significant environmental dependencies.

References

1. Baraffe, I., Chabrier, G., *Astron. Astrophys.*, **521**, A44 (2010)
2. Baraffe, I., Chabrier, G., Gallardo, J., *Astrophys. J.*, **702**, L27–L31 (2009)
3. Beccari, G. et al., *Astrophys. J.*, **720**, 1108–1117 (2010)
4. Bertout, C., Siess, L., Cabrit, S., *Astron. Astrophys.*, **473**, L21–L24 (2007)
5. Burningham, B., Naylor, T., Littlefair, S.P., Jeffries, R.D., *Mon. Not. Roy. Astron. Soc.*, **363**, 1389–1397 (2005)
6. Calvet, N., Briceño, C., Hernández, J., Hoyer, S., Hartmann, L., Sicila-Aguilar, A., Megeath, S.T., D’Alessio, P., *Astron. J.*, **129**, 935–946 (2005)
7. Cieza, L., Baliber, N., *Astrophys. J.*, **671**, 605–615 (2007)
8. Da Rio, N., Gouliermis, D.A., Gennaro, M., *Astrophys. J.*, **723**, 166–183 (2010)
9. Da Rio, N., Robberto, M., Soderblom, D.R., Panagia, N., Hillenbrand, L.A., Palla, F., Stassun, K.G., *Astrophys. J.*, **722**, 1092–1114 (2010)
10. Elmegreen, B.G., *Astrophys. J.*, **530**, 277–281 (2000)
11. Enoch, M.L., Evans, N.J., Sargent, A.I., Glenn, J., *Astrophys. J.*, **692**, 973–997 (2009)
12. Haisch, K. Jr., Lada, E.A., Lada, C.J., *Astrophys. J.*, **553**, L153–L156 (2001)
13. Hartmann, L.W., *Astron. J.*, **121**, 1030–1039 (2001)
14. Hartmann, L., Calvet, N., Gullbring, E., D’Alessio, P., *Astrophys. J.*, **495**, 385–400 (1998)
15. Hernández, J., Hartmann, L., Calvet, N., Jeffries, R.D., Gutermuth, R., Muzerolle, J., Stauffer, J., *Astrophys. J.*, **686**, 1195–1208 (2008)
16. Hillenbrand, L.A., Strom, S.E., Calvet, N., Merrill, K.M., Gatley, I., Makidon, R.B., Meyer, M.R., Skrutskie, M.F., *Astron. J.*, **116**, 1816–1841 (1998)
17. Hillenbrand, L.A., Bauermeister, A., White, R.J., in *14th Cambridge Workshop on Cool Stars, Stellar Systems and the Sun* ed. by G. van Belle, vol. 384 (ASP Conference Series, San Francisco, 2008), p. 200
18. Jeffries, R.D., in *Chemical Abundances and Mixing in Stars in the Milky Way and its Satellites* ed. by S. Randich, L. Pasquini (Springer, Heidelberg, 2006), p. 163
19. Jeffries, R.D., *Mon. Not. Roy. Astron. Soc.*, **381**, 1169–1178 (2007)
20. Jeffries, R.D., Oliveira, J.M., Naylor, T., Mayne, N.J., Littlefair, S.P., *Mon. Not. Roy. Astron. Soc.*, **376**, 580–598 (2007)
21. Littlefair, S.P., Naylor, T., Mayne, N.J., Saunders, E., Jeffries, R.D., *Mon. Not. Roy. Astron. Soc.*, in press, arXiv:1102.3836 (2011)
22. Mercer-Smith, J.A., Cameron, A.G.W., Epstein, R.I., *Astrophys. J.*, **279**, 363–366 (1984)
23. Naylor, T., Jeffries, R.D., *Mon. Not. Roy. Astron. Soc.*, **373**, 1251–1263 (2006)
24. Palla, F., Stahler, S., *Astrophys. J.*, **525**, 772–783 (1999)
25. Palla, F., Stahler, S., *Astrophys. J.*, **540**, 255–270 (2000)
26. Palla, F., Randich, S., Flaccomio, E., Pallavicini, R., *Astrophys. J.*, **626**, L49–L52 (2005)
27. Pflamm-Altenburg, J., Kroupa, P., *Mon. Not. Roy. Astron. Soc.*, **375**, 855–860 (2007)
28. Rebull, L.M., Wolff, S.C., Strom, S.E., *Astron. J.*, **127**, 1029–1051 (2004)
29. Rebull, L.M., Stauffer, J.R., Megeath, S.T., Hora, J.L., Hartmann, L., *Astrophys. J.*, **646**, 297–303 (2006)
30. Sacco, G., Randich, S., Franciosini, E., Pallavicini, R., Palla, F., *Astron. Astrophys.*, **462**, L23–L27 (2007)
31. Siess, L., Dufour, E., Forestini, M., *Astron. Astrophys.*, **358**, 593–599 (2000)
32. Slesnick, C.L., Hillenbrand, L.A., Carpenter, J.M., *Astrophys. J.*, **688**, 377–397 (2008)
33. Tassis, K., Mouschovias, T.Ch., *Astrophys. J.*, **616**, 283–287 (2004)
34. Tout, C.A., Livio, M., Bonnell, I.A., *Mon. Not. Roy. Astron. Soc.*, **310**, 360–376 (1999)
35. Vorobyov, E.I., Basu, S., *Astrophys. J.*, **650**, 956–969 (2006)

